AFRL-RW-EG-TP-2008-7415

High-Bandwidth Measurement and Validation of Bar and Plate Dynamics

Jason Foley – AFRL/RWMF
Jacob Dodson – AFRL/RWMF
Martin Schmidt – AFRL/RWAC
Air Force Research Laboratory
Munitions Directorate
Eglin AFB, FL 32542-6810

Preston Gillespie
Yasmin Besonia
Jacobs Engineering
Eglin AFB, FL 32542-6810

JUNE 2008

CONFERENCE PAPER AND BRIEFING CHARTS

This paper and corresponding briefing charts were presented at the Society of Experimental Mechanics XI International Congress and Exposition on Experimental and Applied Mechanics, held in Orlando, FL on 2-5 June 2008. One or more of the authors are U.S. Government employees working within the scope of their position; therefore, the U.S. Government is joint owner of the work. These charts will not be published in the unclassified conference proceedings. If the Society of Experimental Mechanics (SEM) chooses to publish the paper, it may assert copyright. If so, the U.S. Government has the right to copy, distribute, and use the work by or on behalf of the U.S. Government. Any other form of use is subject to copyright restrictions.

This paper is published in the interest of the scientific and technical information exchange. Publication of this paper does not constitute approval or disapproval of the ideas or findings.

AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE

- **Air Force Materiel Command**
- **United States Air Force**
- **Eglin Air Force Base**

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
JUNE 2008	CONFERENCE PAPER AND BRIEFING CHARTS	

4. TITLE AND SUBTITLE
High-Bandwidth Measurement and Validation of Bar and Plate Dynamics

5a. CONTRACT NUMBER	N/A
5b. GRANT NUMBER	N/A
5c. PROGRAM ELEMENT NUMBER	61102F
5d. PROJECT NUMBER	2302
5e. TASK NUMBER	DM
5f. WORK UNIT NUMBER	06

6. AUTHOR(S)
1) Jason Foley – AFRL/RWMF
Jacob Dodson – AFRL/RWMF
Martin Schmidt – AFRL/RWAC

2) Preston Gillespie
Yasmin Besonia

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
1) Air Force Research Laboratory
Munitions Directorate
AFRL/RWMF
Eglin AFB, FL 32542-6810

2) Jacobs Engineering
Eglin AFB, FL 32542-6810

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RW-EG-TP-2008-7415

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Munitions Directorate
AFRL/RWMF
Eglin AFB, FL 32542-6810

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL-RW-EG

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SAME AS BLOCK 8

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A: Approved for public release; distribution unlimited.
Approval Confirmation for the paper 96 ABW/PA # 03-31-08-186; dated 31 March 2008 and for the charts 05-28-08-270; dated 27 May 2008.

13. SUPPLEMENTARY NOTES
See 'cover page' for pertinent metadata information.

14. ABSTRACT
The Air Force Research Laboratory Munitions Directorate (AFRL/RW) is performing a series of studies to validate the ability of codes to accurately predict the impulse response of simple mechanical structures, i.e., impact-loaded bars and plates, over a wide frequency range. The modal responses of both structures are predicted using finite element codes and simple analytic calculations. An experiment on isolated (i.e., free-free) structures using impulse hammers as the excitation is described. The outputs of high bandwidth strain gages and accelerometers monitor the elastic wave propagation in the structures. The corresponding frequency-domain characteristics (e.g., the power spectral density of each sensor as well as the transfer functions between them) are measured over a wide frequency range in a cylindrical bar. Leakage is found to significantly reduce sensor coherence over a broad spectral band. Use of an exponential window restores the coherence in the original signal, leading to a broadband coherence below 10 kHz, but this approach broadens the modal peaks observed and introduces errors in damping estimates. The initial results from an ongoing effort to characterize the modal response of a hanging plate are also presented.

15. SUBJECT TERMS
Not provided.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			JASON R. FOLEY
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	33	19b. TELEPHONE NUMBER *(Include area code)*

High-bandwidth Measurement and Validation of Bar and Plate Dynamics

Jason R. Foley*, Jacob C. Dodson, and Martin Schmidt
Air Force Research Laboratory
* AFRL/RWMF; 306 W. Eglin Blvd., Bldg. 432; Eglin AFB, FL 32542-5430, jason.foley@eglin.af.mil

Yasmin Besonia and Preston Gillespie
Jacobs Engineering, Inc.

ABSTRACT
The Air Force Research Laboratory Munitions Directorate (AFRL/RW) is performing a series of studies to validate the ability of codes to accurately predict the impulse response of simple mechanical structures, i.e., impact-loaded bars and plates, over a wide frequency range. The modal responses of both structures are predicted using finite element codes and simple analytic calculations. An experiment on isolated (i.e., free-free) structures using impulse hammers as the excitation is described. The outputs of high bandwidth strain gages and accelerometers monitor the elastic wave propagation in the structures. The corresponding frequency-domain characteristics (e.g., the power spectral density of each sensor as well as the transfer functions between them) are measured over a wide frequency range in a cylindrical bar. Leakage is found to significantly reduce sensor coherence over a broad spectral band. Use of an exponential window restores the coherence in the original signal, leading to a broadband coherence below 10 kHz, but this approach broadens the modal peaks observed and introduces errors in damping estimates. The initial results from an ongoing effort to characterize the modal response of a hanging plate are also presented.

INTRODUCTION
Although modeling and simulation (M&S) tools are pervasive for mechanical design, the ability of M&S tools to accurately predict impact loads remains questionable. For example, explicit finite element shock physics codes are not well-characterized for high-frequency coherence. Recent studies [1, 2] have focused on quantifying the long-duration (i.e., many-wavelength) propagation of impulses in simulations; initial results have shown that underlying numerical filtering and roundoff errors cause waves to lose coherence rapidly, especially at high frequencies. This represents a fundamental limitation to predictive analysis of impulsive loading and/or the prediction of high-frequency local resonances in structural assemblies.

This effort represents the initial results from ongoing experimental studies used to validate the efforts of Idesman et al. [3]. Subsequently, the objective is to provide measurements of the vibration and transient response in impact-loaded structures, such as simple bars and plates, from impact loads. The elastic stress wave propagation is characterized using an impulse hammer, strain gages, and accelerometers with high bandwidth measurement techniques (f_c >> 10 kHz); the output is characterized with respect to modal (frequency) as well as transient responses (e.g., the dispersion of the waves).

THEORY
Vibrational Modes
Two systems were studied, a Ti alloy bar (15.2 cm long, 2.54 cm diameter) and an Al alloy plate (61 cm x 122 cm area, 0.6 cm thick). The bar is ASTM Grade 5 (6% Al, 4% V) Ti alloy (ρ = 4.43 g/cm^3, E = 114 GPa, ν = 0.33) and the plate is 2024 Al alloy (ρ = 2.73 g/cm^3, E = 72 GPa, ν = 0.34).

For a simple free-free beam element, the bending modes can be calculated from Harris [4];

$$f_n = \frac{a_n}{2\pi}\sqrt{\frac{EI}{\mu L^4}} \ . \tag{1}$$

where a_n is a constant for the n^{th} mode (where a_n = 22.4, 61.7, and 121 for the first three modes); E is the elastic modulus; $I = \pi d^4/64$ is the area moment of inertia for a right circular cylinder of diameter d; $\mu = A\rho$ is the mass per unit length, and L is the length of the bar. The corresponding predictions are 4.97 kHz, 16.7 kHz, and 26.9 kHz for the first three bending modes.

The first three bending modes calculated by an LS-DYNA eigenvalue analysis (using a coarse mesh with 3350 nodes and 2646 elements) are 4.57 kHz, 11.4 kHz, and 20.0 kHz, shown in Figure 1 below. The first three extensional modes are 16.6 kHz, 33.0 kHz, and 48.9 kHz. Simulations of the free-free plate were also calculated via LS-DYNA eigenvalue analysis; the first ten mode shapes are presented in Figure 2 below.

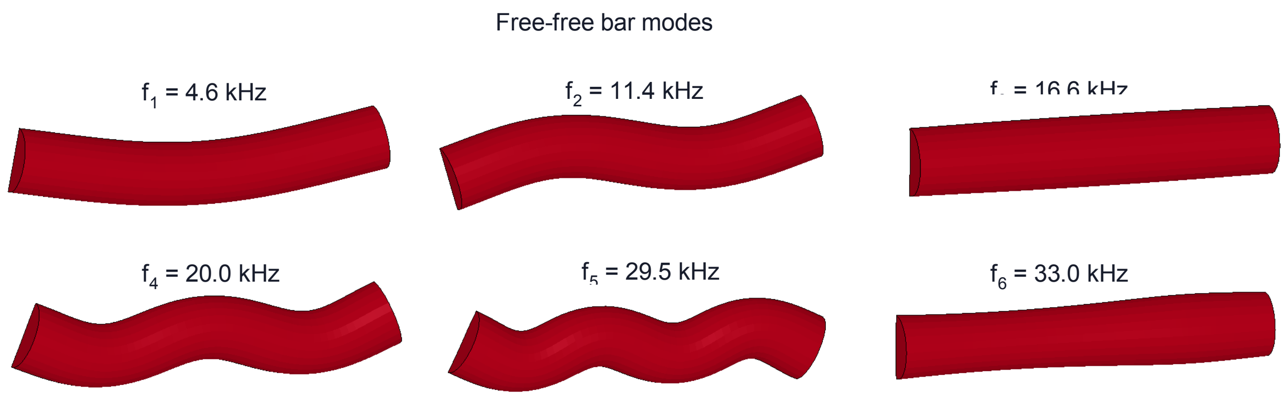


Figure 1. Model predictions of the modal response of the free-free bar.

The longitudinal vibration modes of a free-free bar can be readily calculated using a one-dimensional approximation [5] from the longitudinal elastic wave speed (c) in a bar,

$$c = \sqrt{E/\rho}\,, \tag{2}$$

where ρ is the density of the bar material. Equation (2) gives c = 5072 m/s for the Ti alloy; this gives a traversal time of Δt = 30 μs for a 15.2 cm bar. The corresponding fundamental frequency is

$$f_n = {nc}/{2L}\,, \tag{3}$$

which gives 16.7 kHz and 33.4 kHz for the first two longitudinal modes, closely matching the simulation results.

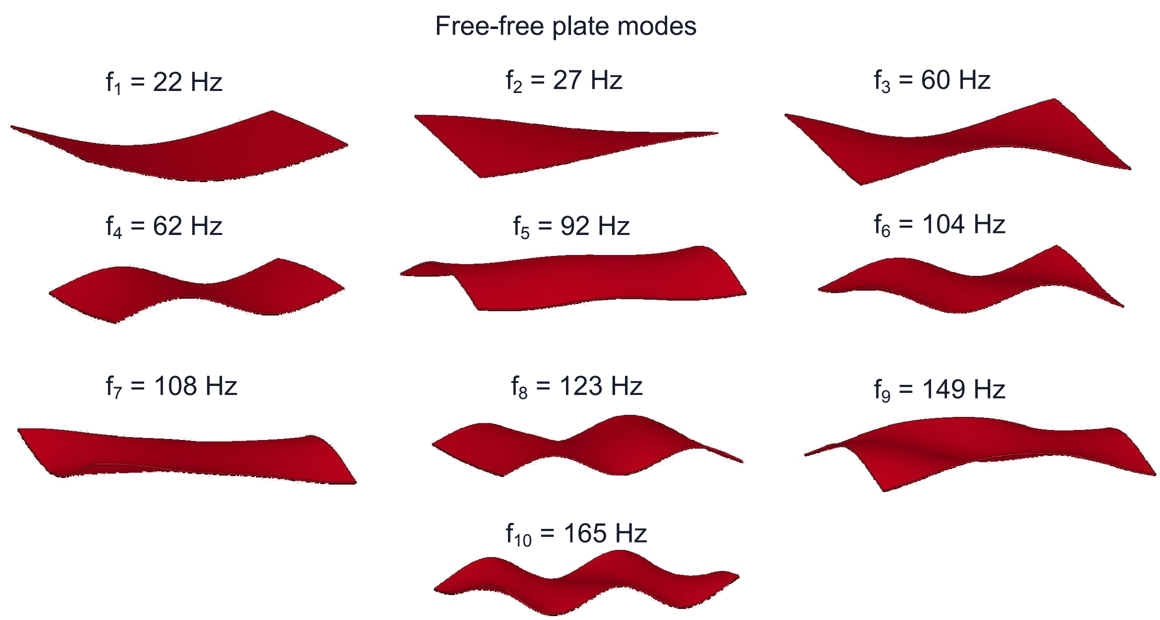


Figure 2. Model predictions of the modal response of the free-free plate.

Transient Analysis

The transfer function is often used to characterize the propagation of elastic waves. The transfer function (also called the frequency response function or FRF) is the frequency-domain relationship between the input and outputs of a specified system and is defined as

$$H(\omega) = \frac{Y(\omega)}{X(\omega)}, \tag{4}$$

where $G(\omega)$ is the transfer function and $X(\omega)$ and $Y(\omega)$ are the frequency-domain input and output, respectively. The transfer function provides information on the relative amplitude of the signals in frequency. Coherence is the ratio of the cross power spectral density (P_{xy}) with the auto spectral densities (P_{xx} and P_{yy}) of the input and output signals [6], i.e.,

$$\gamma_{xy}(\omega) = \frac{\left|P_{xy}(\omega)\right|^2}{P_{xx}(\omega)P_{yy}(\omega)}. \tag{5}$$

The coherence is generally used as an indication of the quality of the data [7], and can be interpreted as a metric to determine if signals are indeed correlated (i.e., all energy is propagated from x to y) without spurious energy sources or sinks.

BAR IMPACT EXPERIMENT, RESULTS, AND DISCUSSION

The Hopkinson split bar technique is well established and widely utilized for research of shock waves [8]. The experimental apparatus is a shortened Hopkinson pressure bar; the aspect ratio is important in this validation experiment because it yields finite element simulations with fewer elements. The excitation for the bar is provided via an ICP impulse hammer (PCB Model 086C01, calibration factor 12.43 mV/N) with a metal tip [9] at the center of the circular face end. To enhance precision and accuracy of the impact, the impulse hammer was suspended in plastic rings to create an impact pendulum. The hammer is raised up to 30 degrees (chosen to avoid channel saturation) and released. Figure 3 depicts the support system of both the impulse hammer and cylindrical bar; the plastic rings and rubber bands minimizes support interaction and approximates a free-free boundary condition.

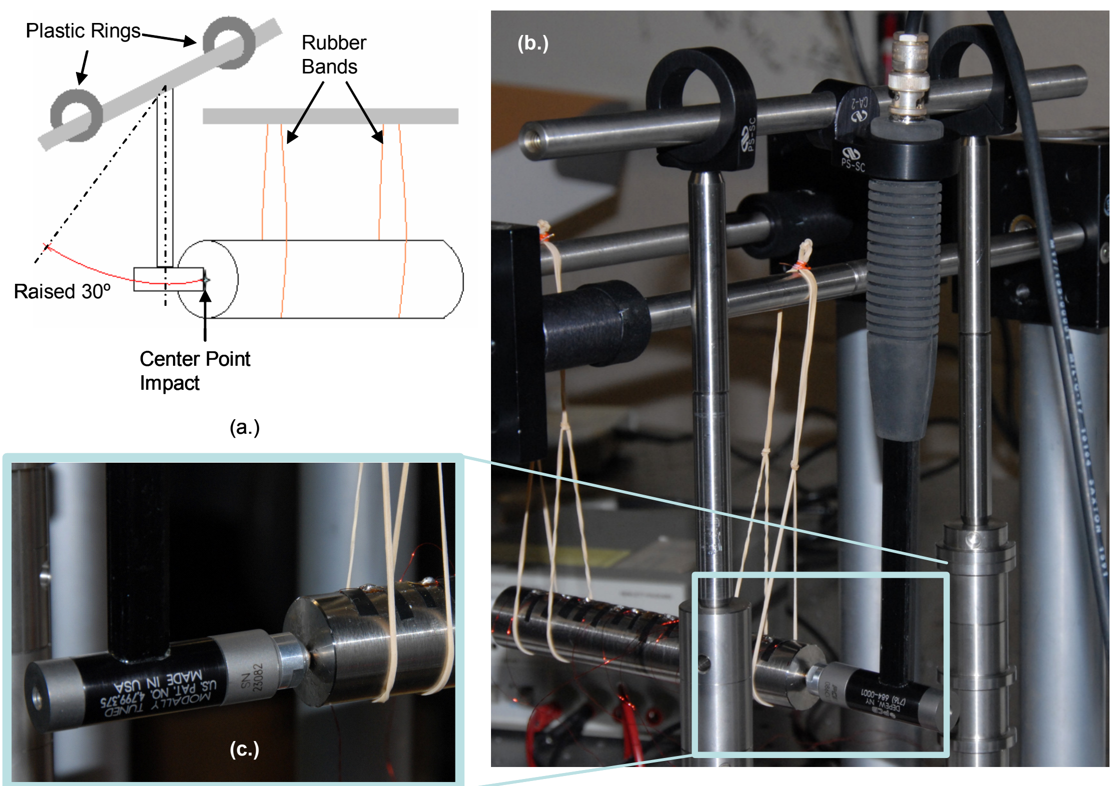
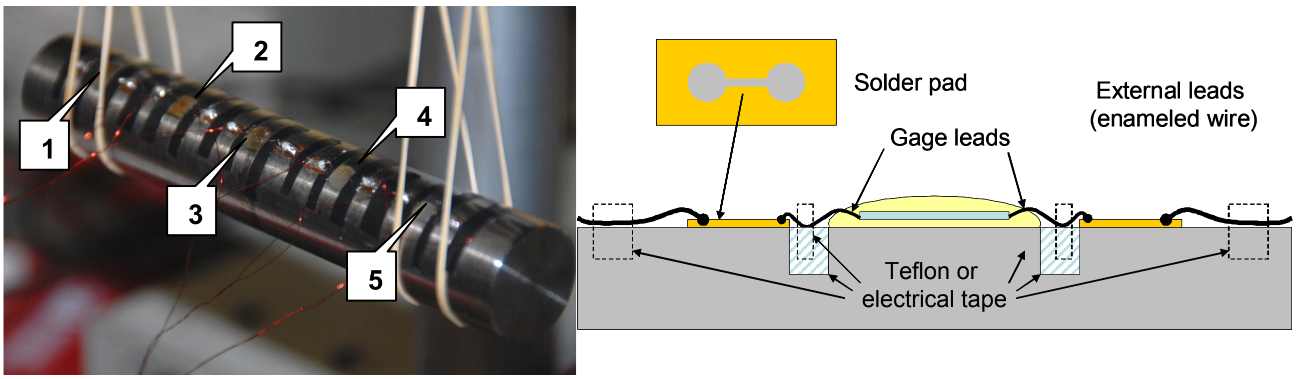


Figure 3. (a.) Schematic of the experimental setup and support system. (b.) Picture of the “pendulum” impact hammer with (c.) detail showing center alignment.

The bar was highly instrumented with sensors to capture the elastic wave propagation and subsequent vibration response. Two types of sensors were used: semiconductor strain gages and piezoresistive accelerometers. An Endevco model 7270A-2k [10] piezoresistive shock accelerometer (2 k*g* full scale, 6.971 $\mu V/m/s^2$ sensitivity, 90 kHz bandwidth) was bolted on the free (non-impacted) end of the bar. The side of the cylindrical bar was instrumented with five semiconductor strain gages, positioned 1 in. apart from each other and the bar ends; the strain gages and their labels are shown in Figure 4(a.). Epoxy was used to mount the strain gages onto the rod (see Figure 4(b.)) and then allowed to cure for 24 hours. The leads were soldered to enamel wire and electrical tape used to ensure there was no electrical contact between the wires and test object. The particular semiconductor strain gages used are Kulite AFP-500-090 bare silicon [11] which have a gage factor of 140 ± 5% at 75 °F and have a nominal resistance of 500 Ω. The rise time of the semiconductor sensors is approximately 100 ns, yielding an effective bandwidth of 5 MHz.



(a.) **(b.)**

Figure 4. (a.) Picture of the instrumented bar under test (the impact face is on the bottom right) and (b.) schematic of the attachment scheme for the semiconductor strain gages.

Typical data from the impact testing is shown in Figure 5 below; the data is shown for one test from the accelerometer, strain gages, and the force hammer. The data is filtered at 50 kHz to aid visualization. The time domain traces show a distinct time-of-arrival delay relative to the initial elastic wave. The inset of Figure 5 shows that a quick estimate of the delay is approximately 32 μs, which is in close agreement with the calculation from Eq. (2). The modal response of the structure is also immediately obvious. Another obvious feature from the time history is that strain gage 3 has the largest amplitude due its center placement on the bar; it experiences maximum bending for the first two modes whereas strain gages 1 and 5 have much lower relative displacement.

The frequency response of the structure is shown as a power spectral density of the sensor output in Figure 6 (using a Matlab routine based on a spectral estimating technique by Welch [12]). The mode structure is immediately obvious with the first several modes easily discernible. These values match closely to the analytic and computational mode predictions (see Figure 1). It is also important to note the bandwidth of the sensors is only due to the global roll-off from the low-pass filtering at a corner frequency of 50 kHz. The only exception is the impulse hammer, which has a bandwidth of approximately 9.5 kHz with a metal tip. However, leakage is apparent in the broadened peaks.

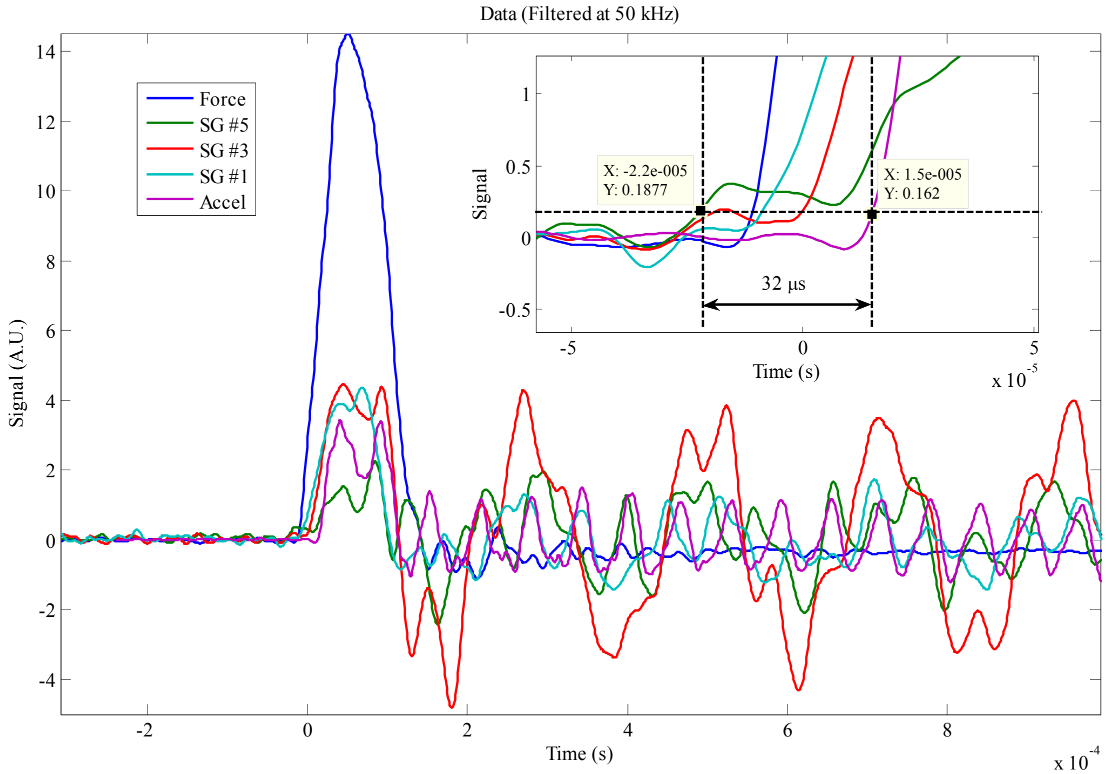


Figure 5. Sensor output (filtered at 50 kHz) from the force hammer, strain gages, and accelerometer. The time-of-arrival of the elastic wave (inset) is approximately 32 μs, which agrees with the predicted time of 30 μs.

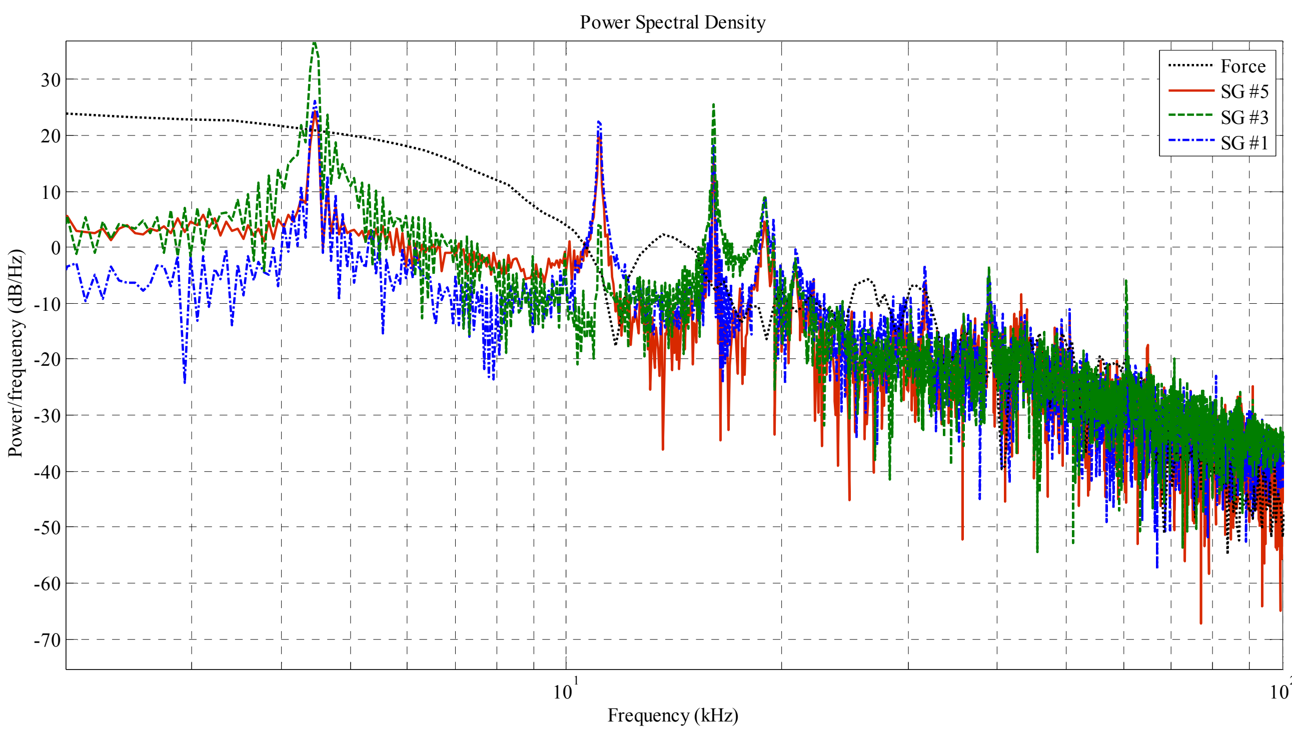


Figure 6. Estimated power spectral density of the various channels from the entire time history. All data is filtered at 50 kHz.

The transfer functions were initially determined between strain gages 5 to 3, 3 to 1, and 5 to 1 to evaluate the quality of the experimental data; the data is shown in Figure 7. The transfer functions exhibited a strong relative amplification or attenuation near the principle modes as would be expected from the particular bending and extensional mode shapes and the sensors different locations on the bar. However, examining the coherence between the measurements in Figure 8 show that the coherence is limited to extremely narrow frequency bands with coherence ~1, supporting the earlier observation that leakage is dominating the signals.

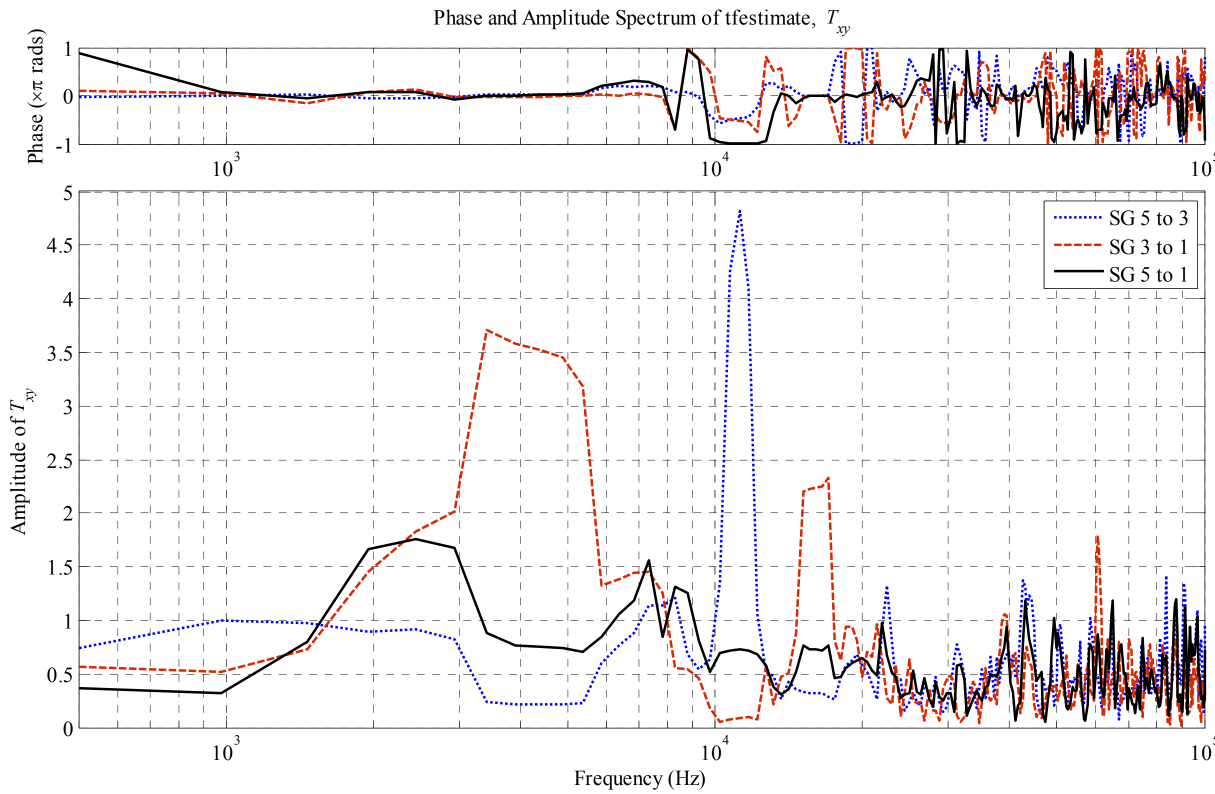


Figure 7. Transfer function estimate between the strain gages (data is filtered at 50 kHz).

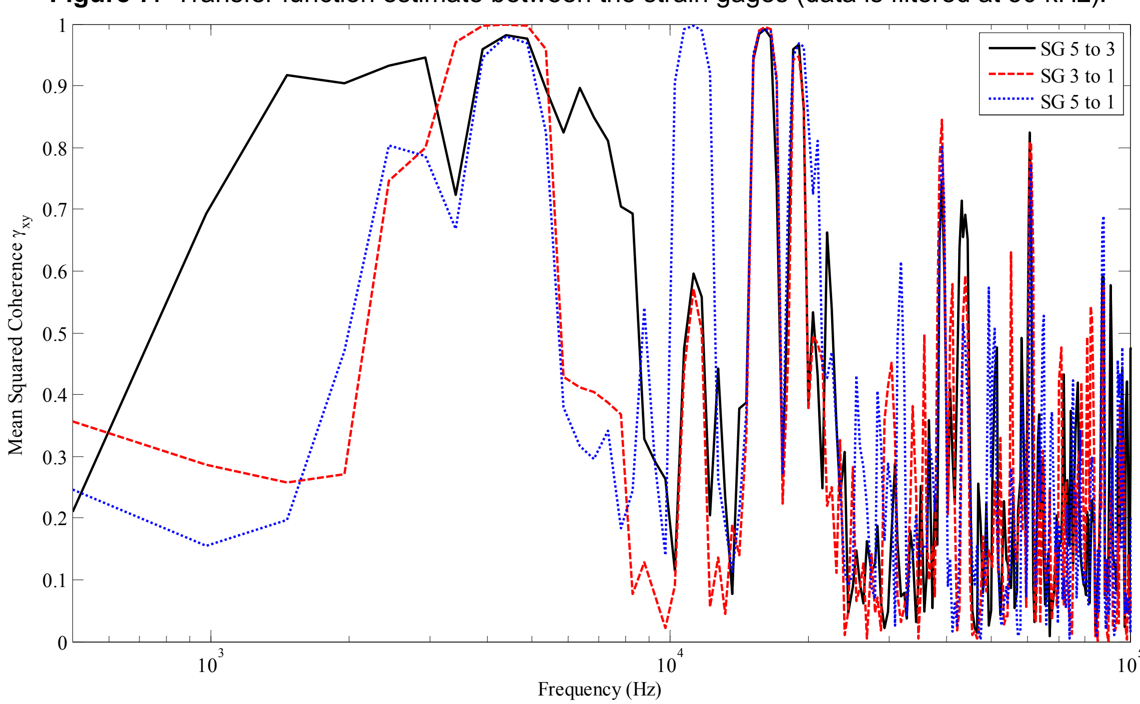


Figure 8. Mean-squared coherence of the data in Figure 5 (data is filtered at 50 kHz).

Windowing is typically performed on sampled data to reduce the effect of leakage when the FFT is used on discrete data where the time history does not attenuate to a negligible in the total sample time. The time history from this weakly-damped system has these characteristics and is windowed using an exponential (Gaussian) decay window [13] can be applied to the response to attenuate the signal at the signal beginning and end in the time domain. This introduces a Gaussian convolution in the frequency domain and correspondingly broadens the spectral response and makes it difficult to estimate of the dampening for the modes. The results of the windowing (using an exponential decay time constant of 450 μs) on the coherence are shown in Figure 9 below. It is evident that all of the measurements—impulse hammer, strain gage, and accelerometer—are coherent below 10 kHz. The filtering and higher modal density makes the coherence difficult to evaluate above 10 kHz; this is the subject of continuing studies and is beyond the scope of this paper.

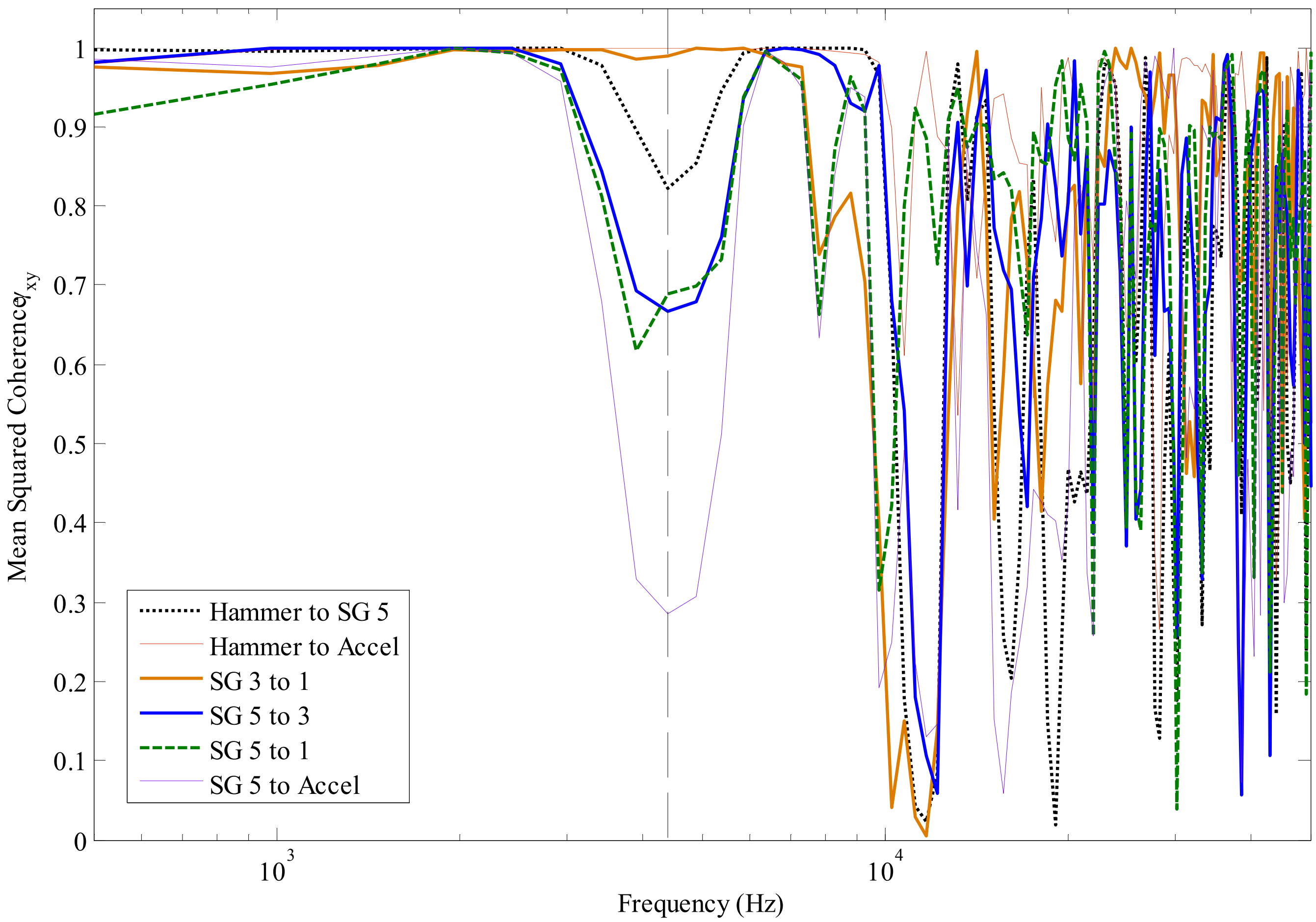


Figure 9. Mean-squared coherence of the data in Figure 5 (filtered at 50 kHz) using an exponential window.

PLATE IMPACT RESULTS, ANALYSIS, AND DISCUSSION

In addition to the short bar impact tests, similar analysis was performed on a hanging plate. The plate was suspended using elastic cables and instrumented with several Endevco 7270A-2k shock accelerometers. The excitation was provided via an ICP modal sledgehammer. The frequency response functions (FRF's) are measured on a grid using a roving sensor, fixed input approach. Representative data is shown in Figure 10(a.) and (b.). The peaks in the FRF correspond with bending modes predicted in Figure 2.

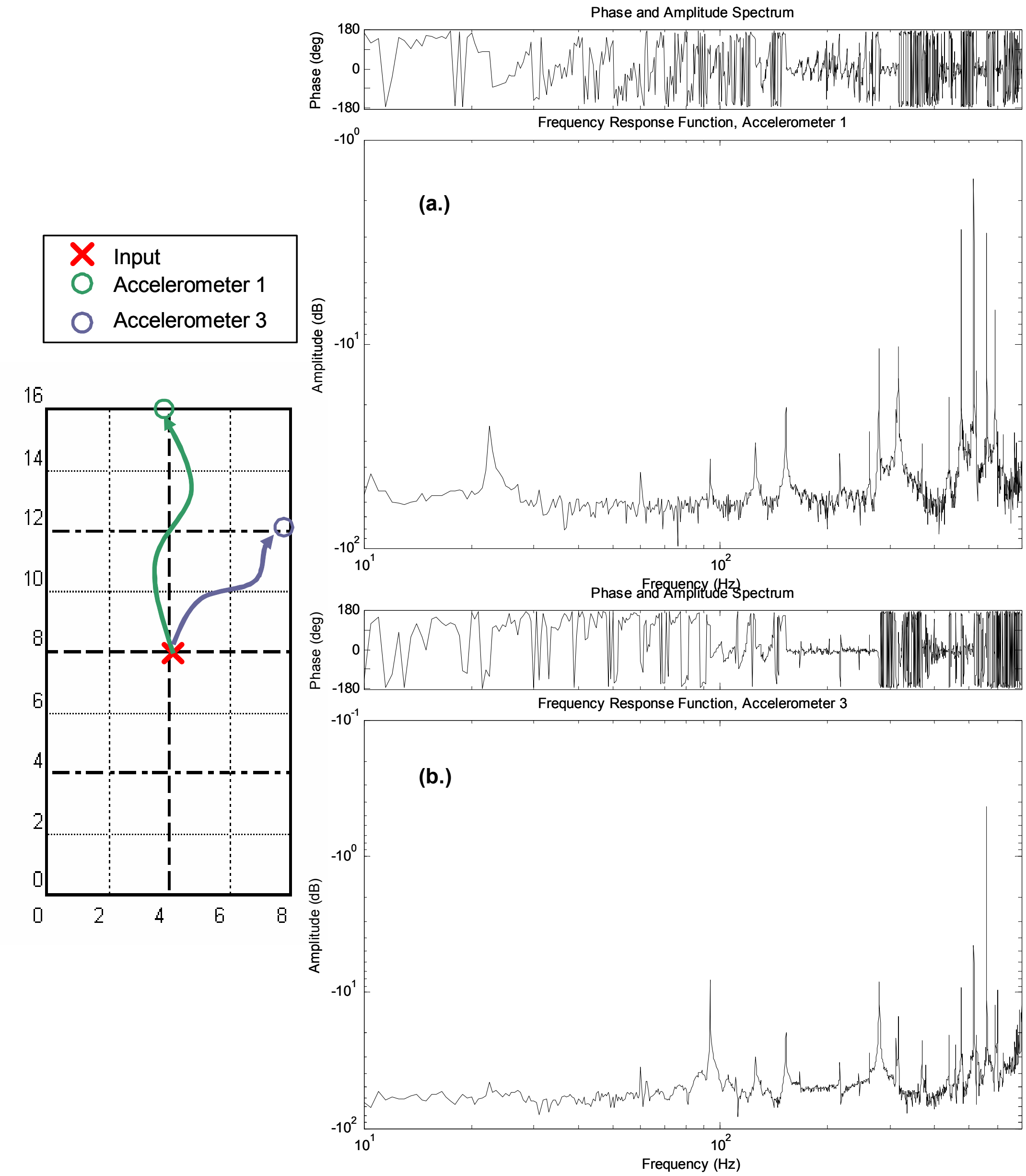


Figure 10. Schematic and representative data for the frequency response function data obtained from a hanging plate experiment.

A quick estimate of the plate parameters (i.e., dynamic characteristics) was desired from the experimental data, notably the mode shapes, natural frequencies (ω), and structural dampening (ξ). The FRF's were estimated using a simple rational fractional polynomial (RFP) method [14]. The results for many modes simultaneously estimated over a wide frequency range are shown in Figure 11 below. Several peaks have good estimates, yet several others are not accurately captured by the modal estimates. The preliminary modal analysis results presented here are insufficient as a characterization of the mode structure, but the initial indications are that some of the bending modes are being predicted accurately. A more extensive analysis focused on the hanging plate using rigorous modal analysis techniques is ongoing and will be reported in a future paper.

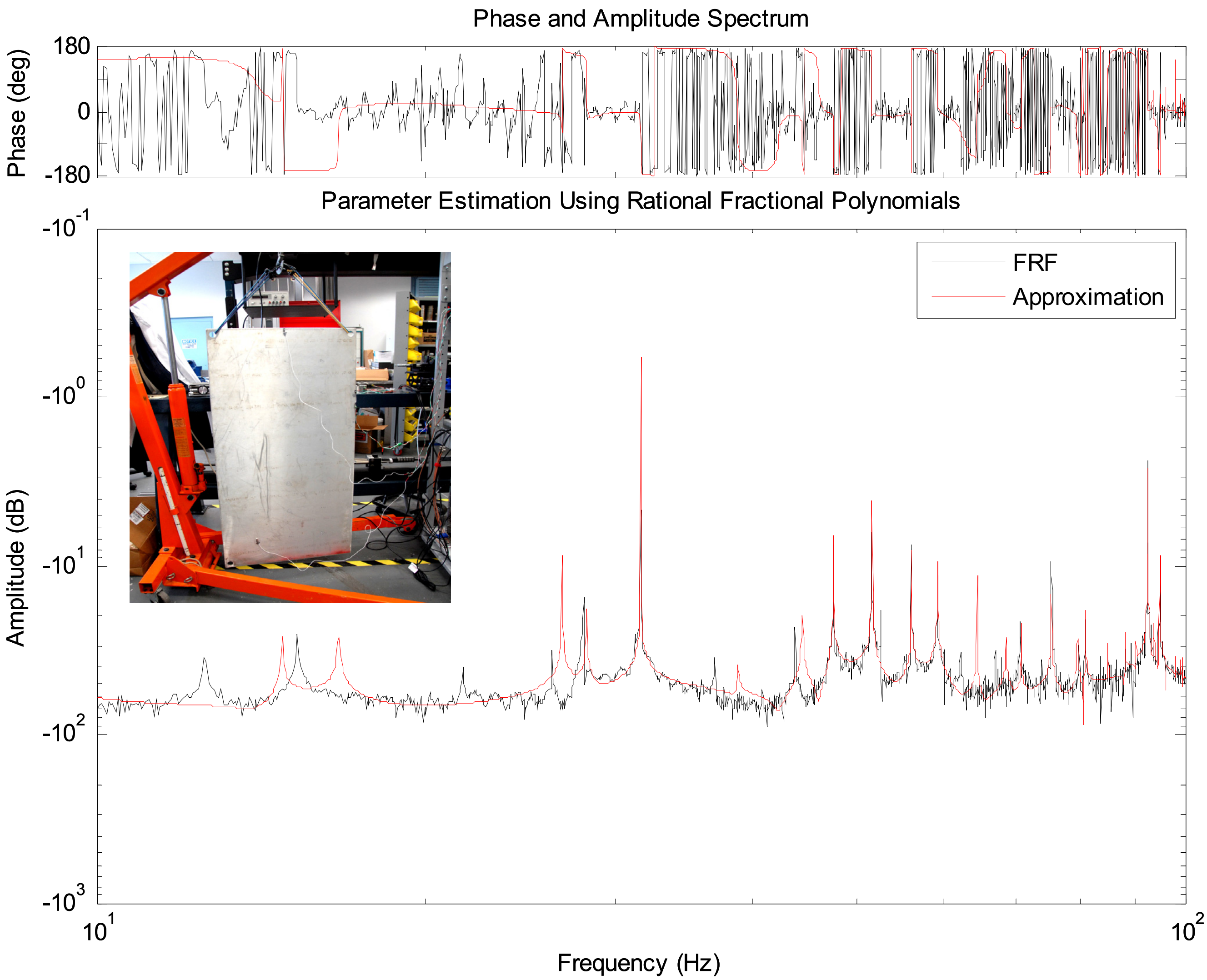


Figure 11. Estimates on the mode structure of the hanging plate (inset picture) using a rational fractional polynomial parameter estimation algorithm.

FUTURE WORK

As noted earlier, several observations were made that require further experimental investigation. New data acquisition hardware is being used to capture the entire impact and subsequent decay at maximum bandwidth. Additional sensor sets are also being examined; for example, the experimental apparatus is being modified to include integrated quartz crystals to create effective load cells (see refs. [15-17]). An ultra-high bandwidth (8 GHz) photonic doppler velocimeter (PDV) [18] is also being tested for surface-normal velocity measurements; this provides a direct indication of the velocity for both modal estimation and computational validation. The results from these studies on simple structures will inform the development and implementation of higher accuracy methods for numerical dispersion and continue with studies into the shock-response behavior of complex structures with interfaces.

SUMMARY

The dynamics response of simple bar and plate structures were predicted using a combination of analytic calculations and finite element simulations. Experiments to reproduce the free-free boundary conditions on a bar and plate were described. The structures were excited by impact from impulse hammers; the outputs of high bandwidth strain gages and accelerometers were monitored to determine the elastic wave propagation in the structures as well as the corresponding frequency-domain characteristics: power spectral density, transfer functions, and coherence. Leakage was found to significantly reduce sensor coherence over a broad spectral band, but the use of an exponential window restored the coherence in the original signal. Using this approach, a broadband coherence was obtained up to approximately 10 kHz. However, resultant broadening of the modal peaks alters the apparent damping, illustrating the difficulty in maintaining coherence in a laboratory setting. The initial results from an ongoing effort to characterize the modal response of a hanging plate were also presented along with an estimate of the modal parameters.

ACKNOWLEDGEMENTS
Y. B. and J. D. would like to thank Mark Lynch and the Eglin TEAS Team (Jacobs Engineering, Inc.) for providing the summer research internships through which some of this work was performed. J. D. is also supported by Department of Defense SMART (Science, Mathematics, And Research Transformation) scholarship program. Finally, J. F. acknowledges research funding from Dr. Victor Giurgiutiu of the Air Force Office of Scientific Research (AFOSR).

Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.

REFERENCES

[1] A. V. Idesman, "Solution of linear elastodynamics problems with space-time finite elements on structured and unstructured meshes," *Computer Methods in Applied Mechanics and Engineering,* **196** (9-12), pp. 1787-1815, 2007.

[2] A. Idesman, "A new high-order accurate continuous Galerkin method for linear elastodynamics problems," *Computational Mechanics,* **40** (2), pp. 261-279, 2007.

[3] A. V. Idesman, M. Schmidt, and R. L. Sierakowski, "A new explicit predictor-multicorrector high-order accurate method for linear elastodynamics," *Journal of Sound and Vibration,* **310** (1-2), pp. 217-229, 2008.

[4] C. M. Harris and A. G. Piersol, "Shock and Vibration Handbook," 5th ed New York: McGraw-Hill, 2002.

[5] D. J. Inman, *Engineering Vibration*. Upper Saddle River: Pearson, 2008.

[6] G. Carter, C. Knapp, and A. Nuttall, "Estimation of the magnitude-squared coherence function via overlapped fast Fourier transform processing," *Audio and Electroacoustics, IEEE Transactions on,* **21** (4), pp. 337-344, 1973.

[7] V. I. Bateman, F. A. Brown, and M. A. Nusser, "High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6," Sandia National Laboratory Report SAND2000-1528 July 2000.

[8] D. J. Parry, A. G. Walker, and P. R. Dixon, "Hopkinson bar pulse smoothing," *Measurement Science and Technology,* **6** (5), pp. 443-446, 1995.

[9] "086C01 ICP Impact Hammer Data Sheet," PCB Piezotronics, Inc. 2004.

[10] "Model 7270A Accelerometer Data Sheet," Endevco Corporation 2005.

[11] *Kulite Strain Gage Manual*: Kulite Semiconductor Products, 2001.

[12] P. Welch, "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," *Audio and Electroacoustics, IEEE Transactions on,* **15** (2), pp. 70-73, 1967.

[13] F. J. Harris, "On the use of windows for harmonic analysis with the discrete Fourier transform," *Proceedings of the IEEE,* **66** (1), pp. 51-83, 1978.

[14] A. Carcaterra and W. D'Ambrogio, "An iterative rational fraction polynomial technique for modal identification," *Meccanica,* **30** (1), pp. 63-75, 1995.

[15] R. J. Wasley, K. G. Hoge, and J. C. Cast, "Combined Strain Gauge---Quartz Crystal Instrumented Hopkinson Split Bar," *Review of Scientific Instruments,* **40** (7), pp. 889-894, 1969.

[16] B. Song, W. W. Chen, S. Dou, N. A. Winfree, and J. H. Kang, "Strain-rate effects on elastic and early cell-collapse responses of a polystyrene foam," *International Journal of Impact Engineering,* **31** (5), pp. 509-521, 2005.

[17] W. Chen, F. Lu, and B. Zhou, "A quartz-crystal-embedded split Hopkinson pressure bar for soft materials," *Experimental Mechanics,* **V40** (1), pp. 1-6, 2000.

[18] O. T. Strand, L. V. Berzins, D. R. Goosman, W. W. Kuhlow, P. D. Sargis, and T. L. Whitworth, "Velocimetry using heterodyne techniques," *Proc. SPIE,* **5580** (pp. 593-599, 2005.

High-Bandwidth Measurement and Validation of Bar and Plate Dynamics

SEM XI International Congress and Exposition on Experimental and Applied Mechanics

Orlando, FL

4 June 2008

Dr. Jason Foley, Jacob Dodson, and Dr. Martin Schmidt

Air Force Research Laboratory, Munitions Directorate

Preston Gillespie and Yasmin Besonia

Jacobs Engineering

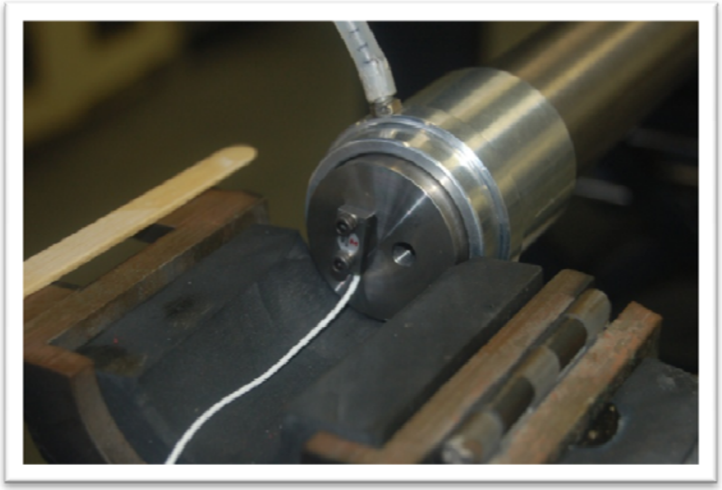
AFRL

THE AIR FORCE RESEARCH LABORATORY

LEAD I DISCOVER I DEVELOP I DELIVER

Outline

- Research Objectives
- Bar Impact
  - Simulation
  - Experiment
- Plate Impact
  - Simulation
  - Experiment
- Summary
- Acknowledgements

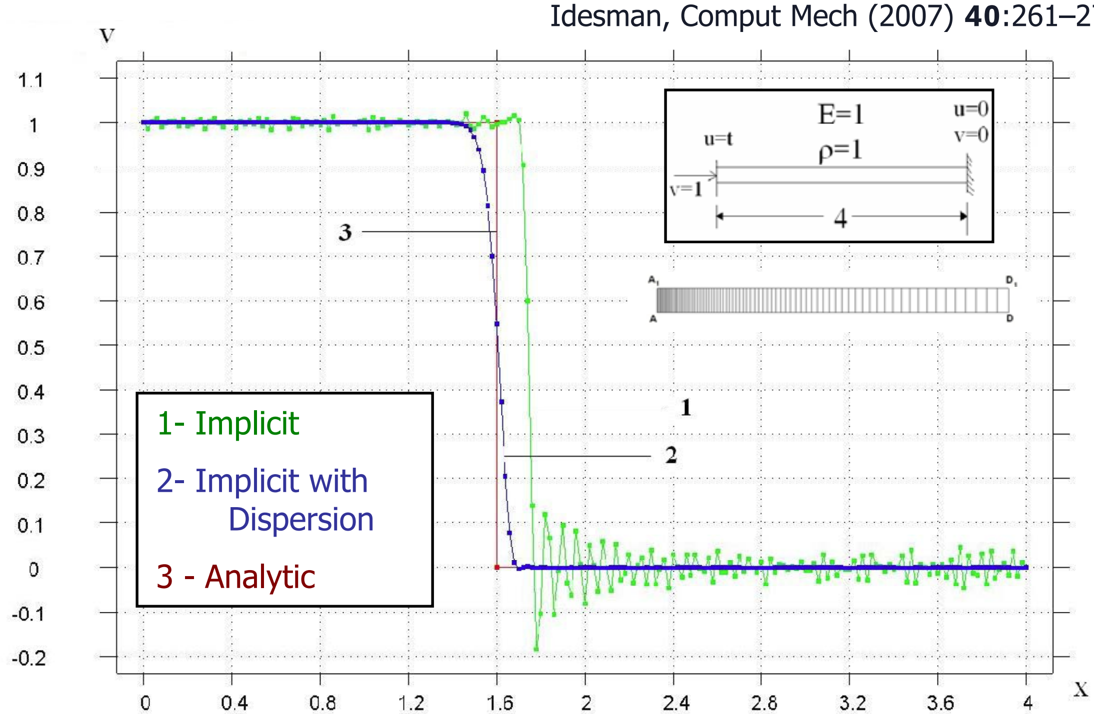


Research Objectives

Idesman, Comput Mech (2007) **40**:261–279

Research Challenge:

- Current models and numerical methods do not agree with experiments at high frequencies
  - *f* >10 kHz
  - Can't predict resonant excitation



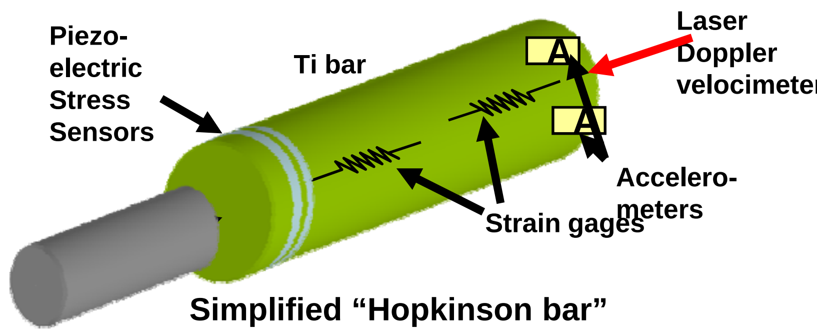
Linear, Elastodynamic Simulation of Bar Impact

Research Objectives:

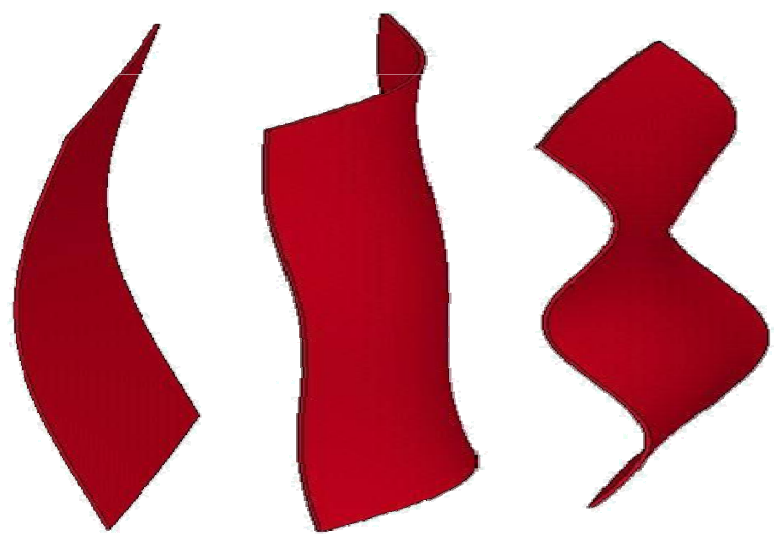
- Quantify the ability of "hydrocodes" and other M&S capabilities to capture full spectrum using analytic cases
- Validate predictions using controlled experiments

Approach

- Perform "simple" validation experiments
  - Simplified "Hopkinson bar"
  - Resonating Plate
- Apply impulsive loads
  - Strain rates ~10^2-10^4 s^{-1}
  - Force » 100 N
- Use high bandwidth measurement techniques
  - f > 10 MHz



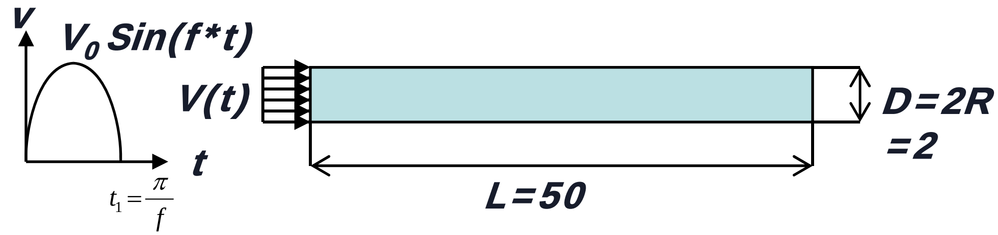
Simplified "Hopkinson bar"



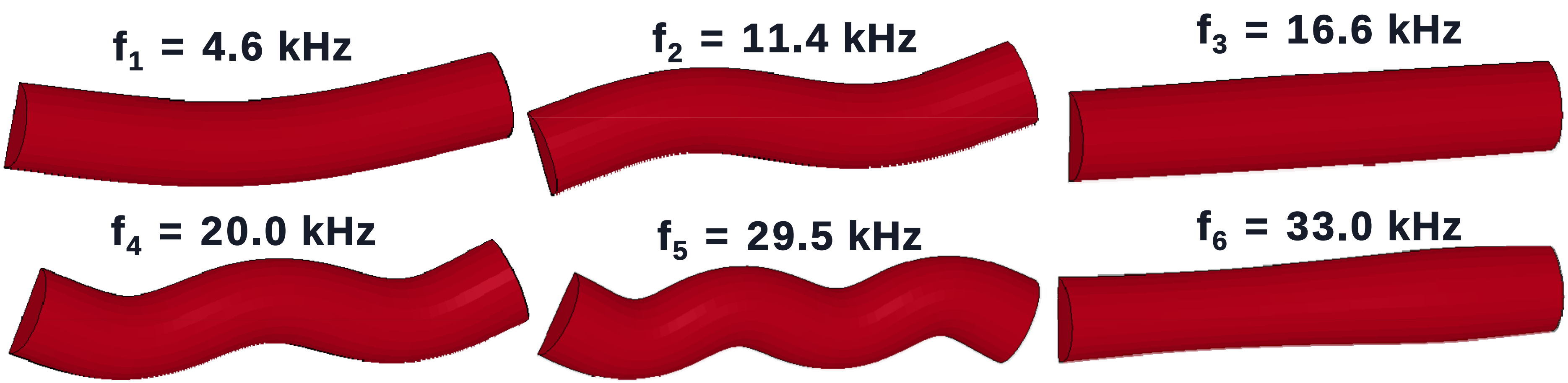
Resonating Plate

Bar Impact M&S

- Work by Idesman
  - Axisymmetric FEA
  - Measured dispersion
  - Compared with 1-D theory (no dispersion)
- Modal analysis using LS-DYNA



Free-free bar modes



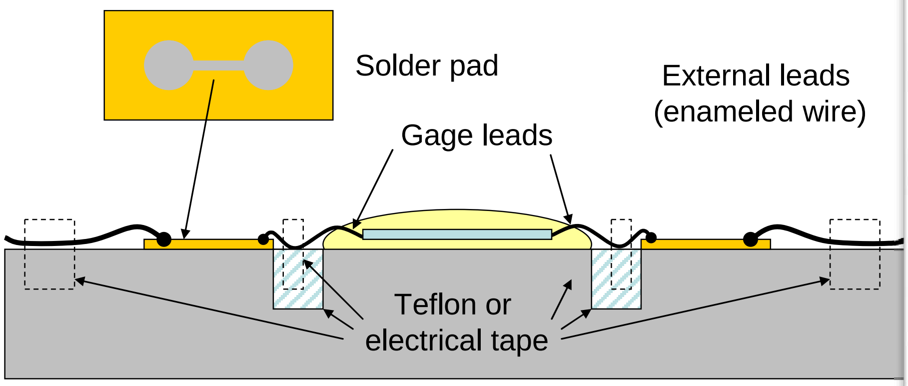
Bar Impact Experiment

<u>Simplified Bar Experiment</u>

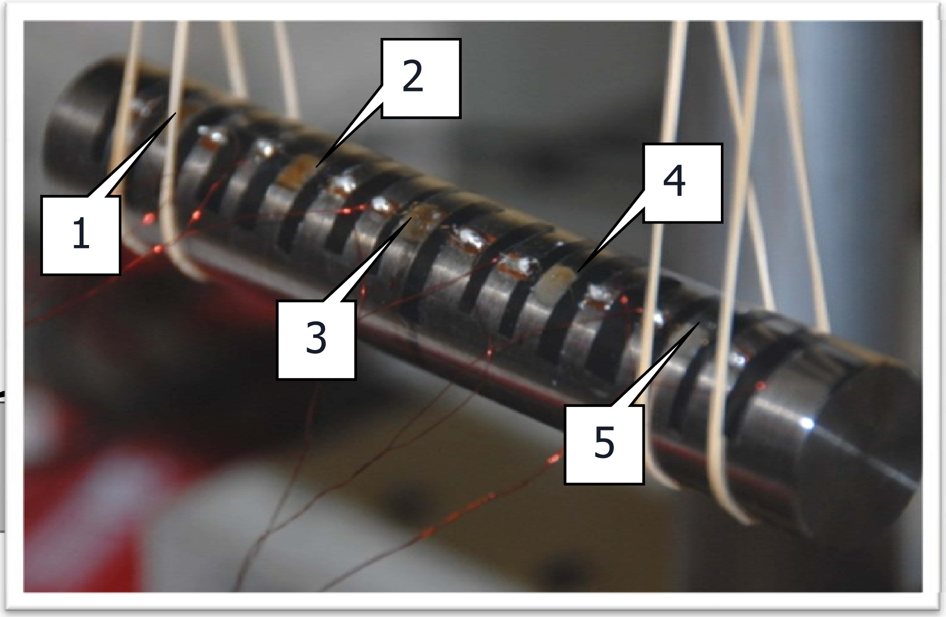
- Short length to accommodate high mesh densities
- Known material properties
  - Ti alloy (6% Al, 4% V) grade 5
  - Length: 6 in.
  - Diameter: 1 in.
  - Weight: 0.754 lbs.

<u>Sensors</u>

- Semiconductor Strain Gage
  - 5 mounted with epoxy
  - Resistance of 500 Ω
  - Gage factor of 140 ± 5% at 75°F
- Piezoresistive accelerometer
  - Full scale of 2 k*g*
  - Hard-mounted on end of bar

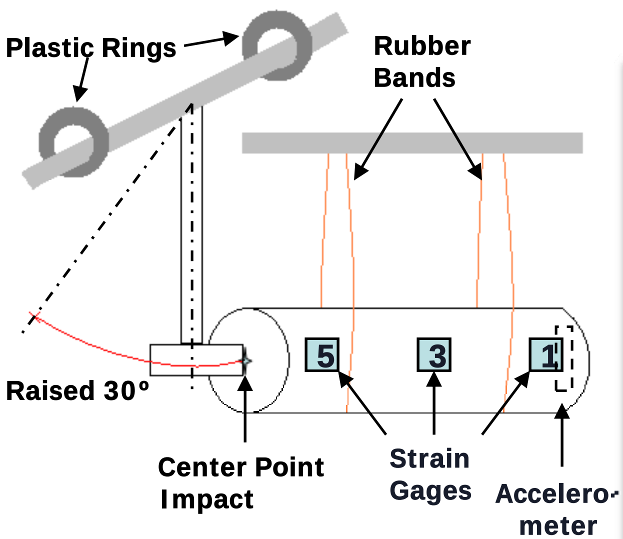


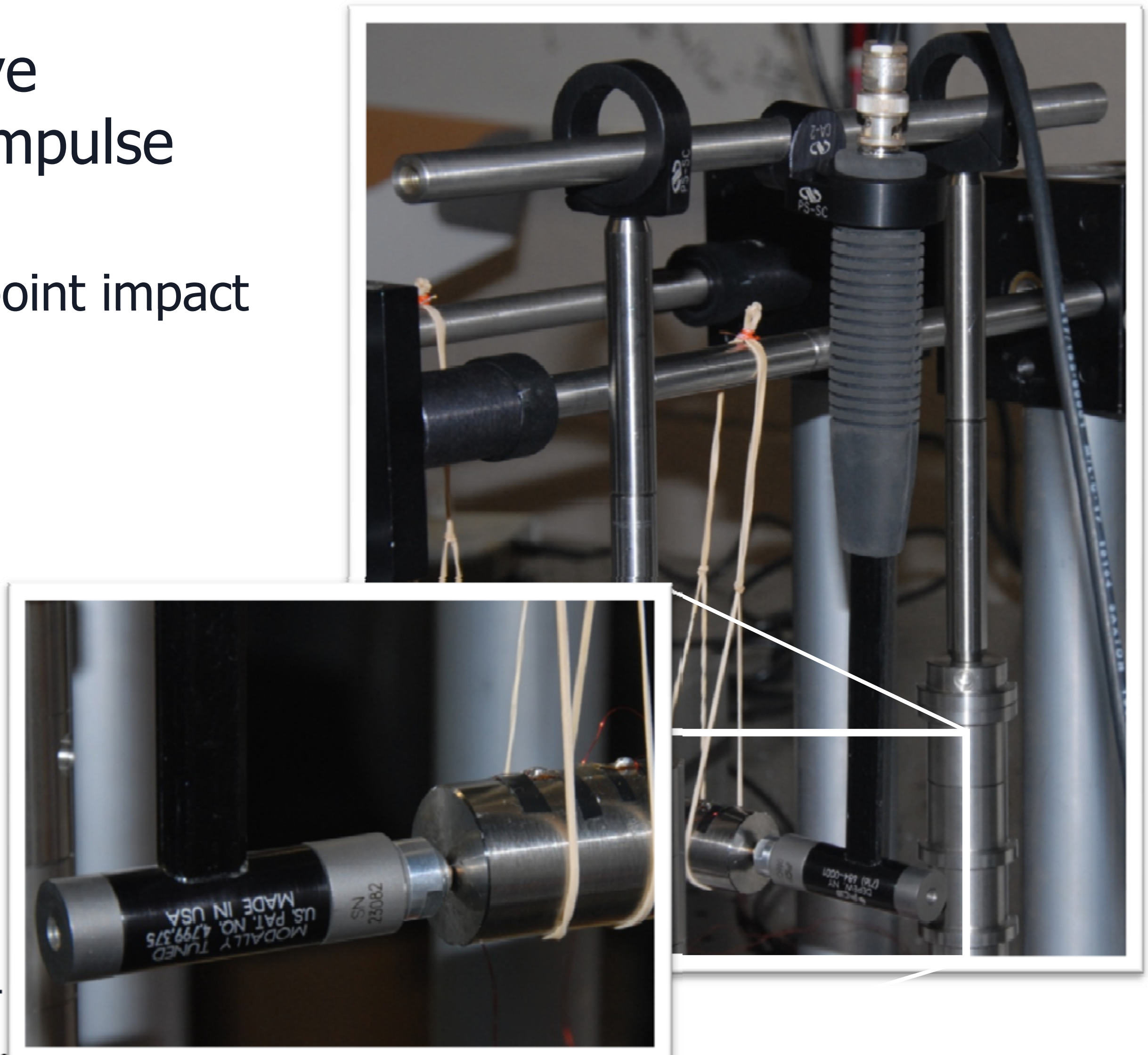
Schematic of Strain Gage Attachment



Bar Impact Experiment

- Elastic stress wave introduced with impulse hammer
  - Assume center point impact
  - Metal tip used





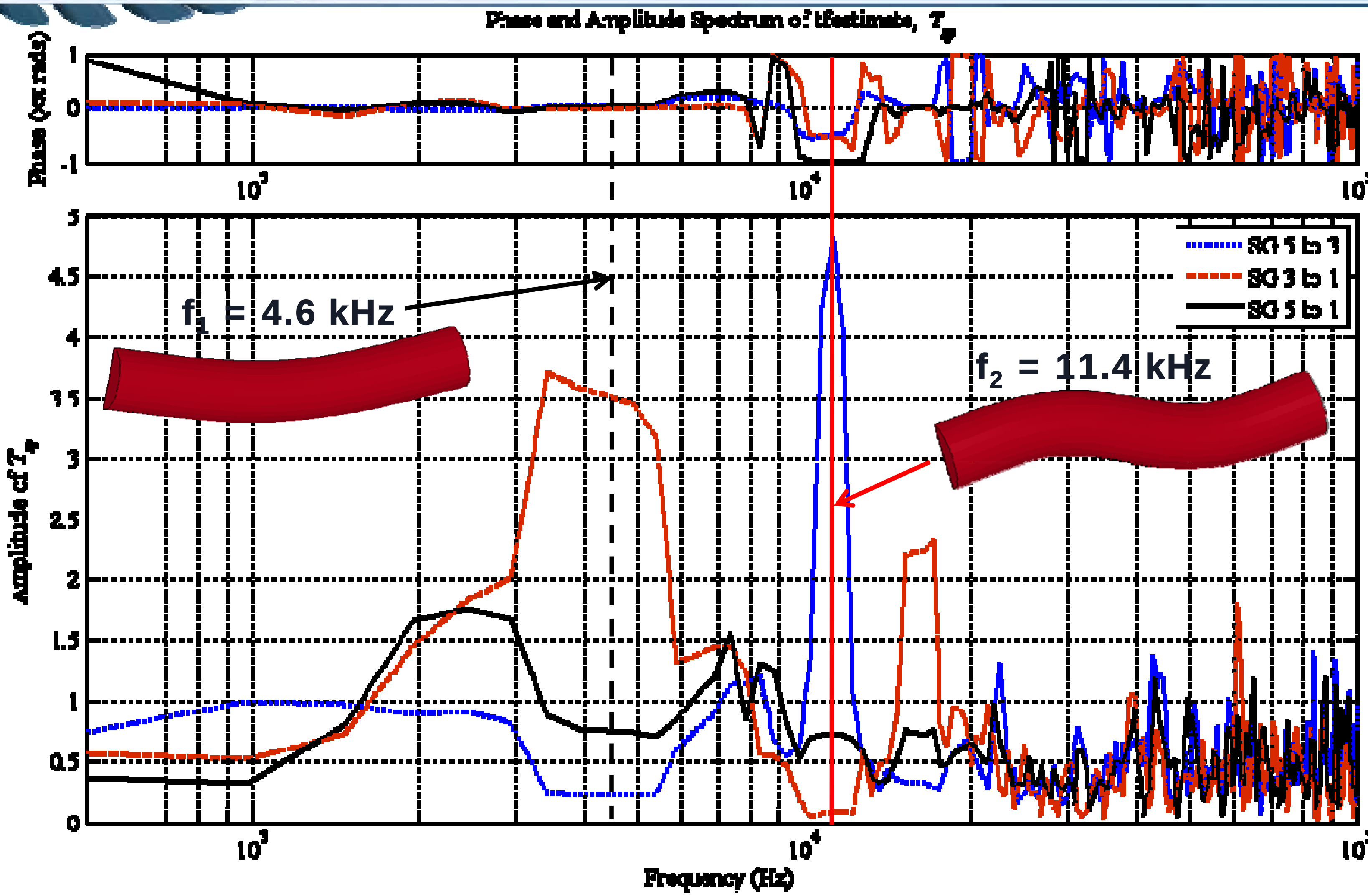
Data Analysis

- Analyzed data using signal processing tools
  - PSD
  - Transfer function
  - Coherence

- Coherence is measure of correlation between response and input (stimulus) energy
  - Noise
  - Causality

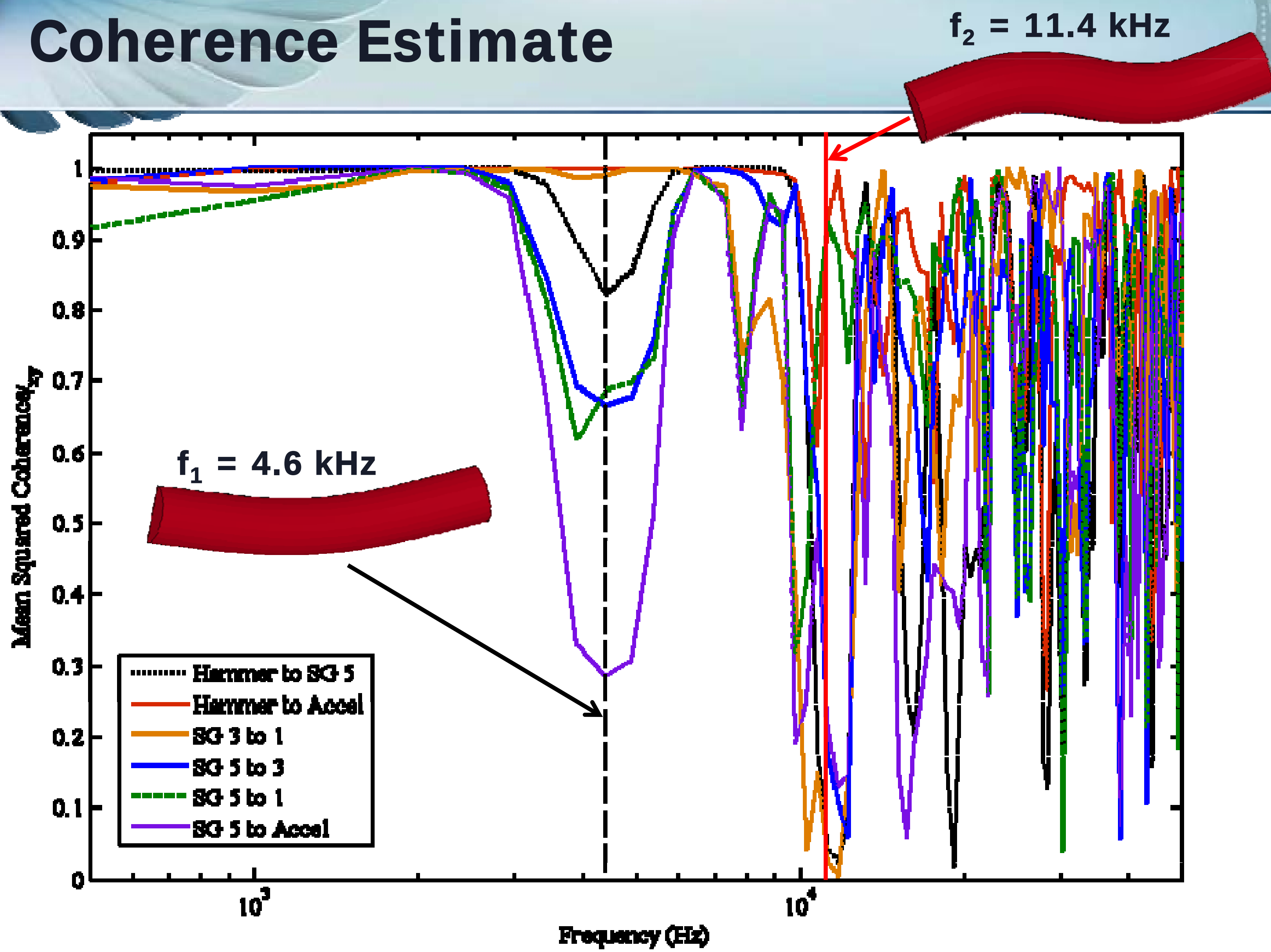
$$C_{ij} = \frac{\left|P_{ij}(f)\right|^2}{P_{ii}(f)P_{jj}(f)}$$

Transfer Function Estimate



Transfer function estimate between the strain gages (data is filtered at 50 kHz).

Coherence Estimate



Mean-squared coherence (data is filtered at 50 kHz).

Bar Impact Observations

- Long sampling time required for low frequency
  - Very long record lengths
  - Competes with bandwidth
- Small size of bar creates challenges for sensor density
- M&S requires very fine meshes
  - Results in very long simulation times
- Experiment data much higher fidelity and coherence

Even ***simple cases*** *are computationally expensive to run and* ***do not agree with validation experiments*** *under impact loads*

Plate Impact M&S

- LS-DYNA Simulations
  - Modal analysis
  - Plate impact

Free-free plate modes

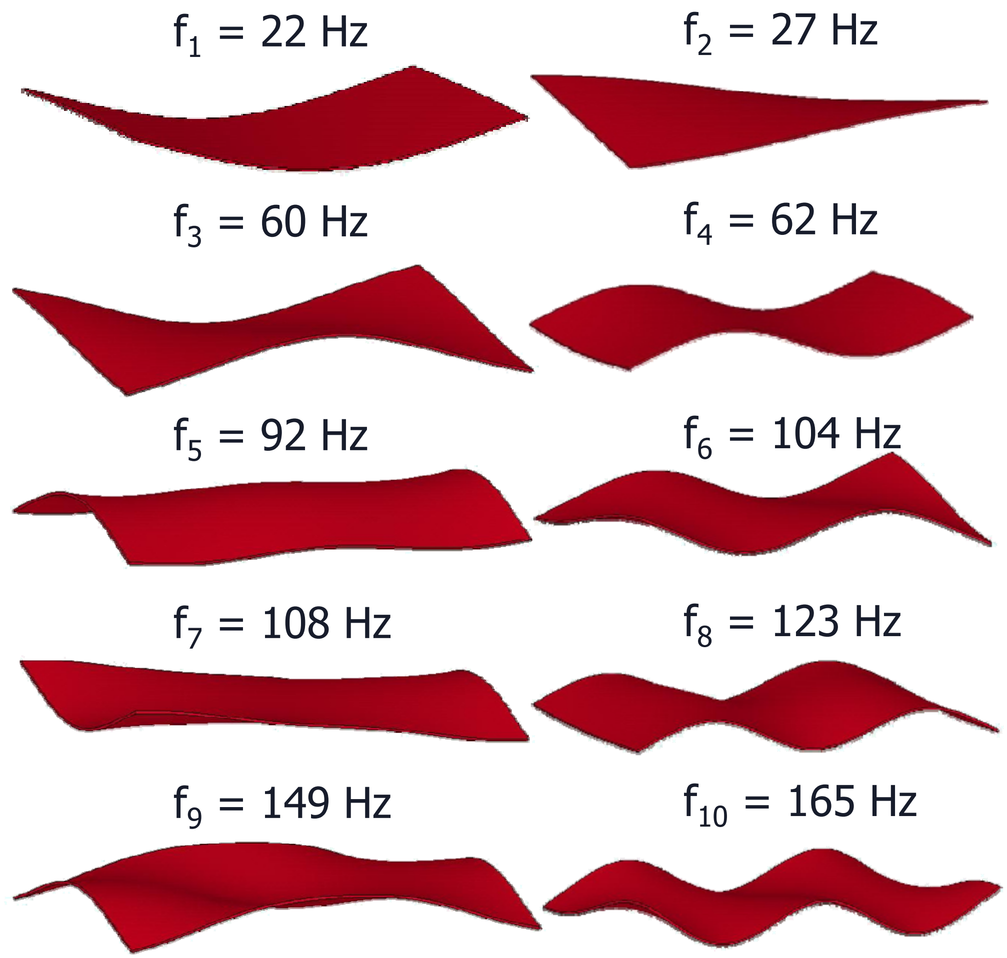
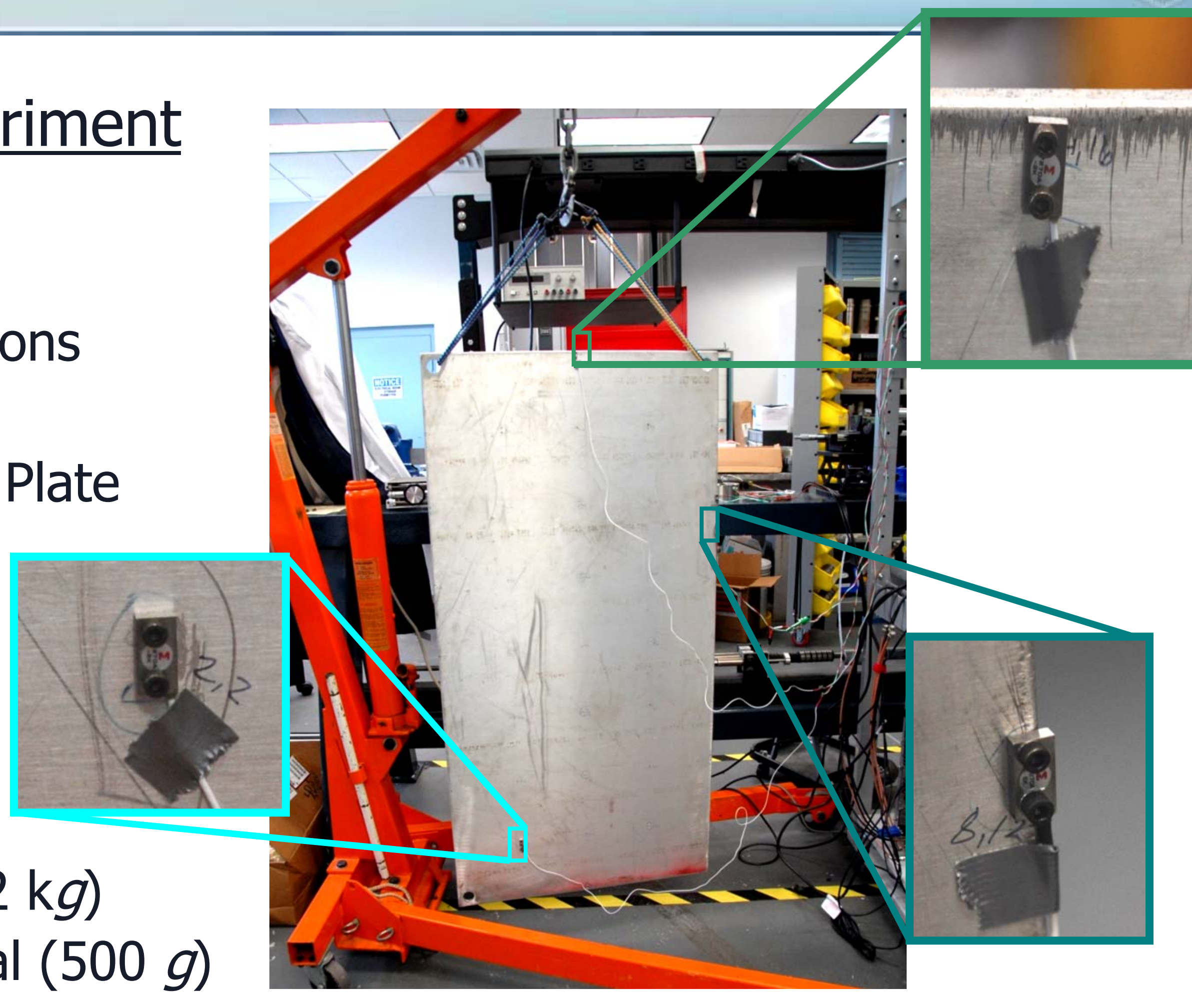


Plate Impact Experiment

Simplified Plate Experiment

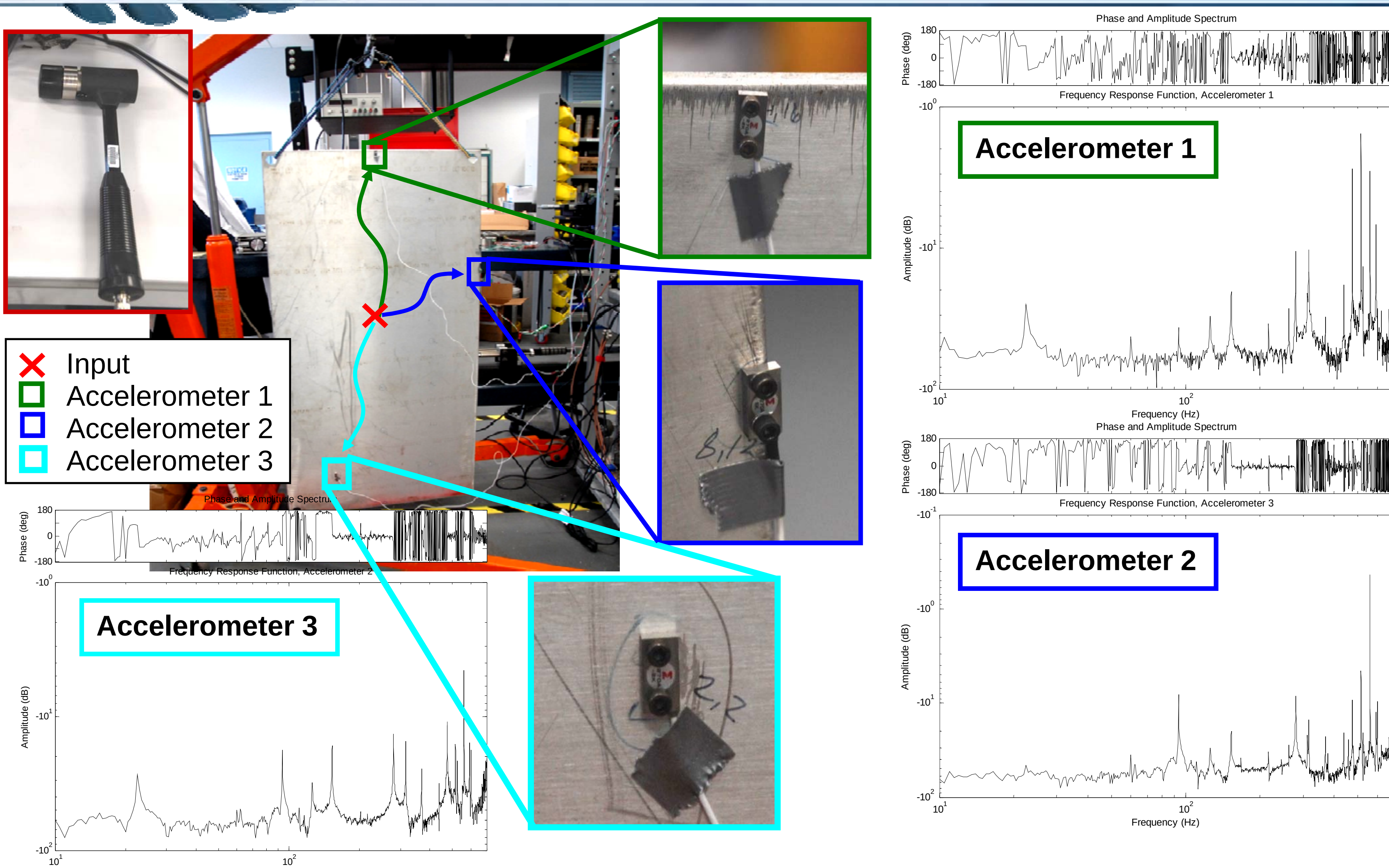
- Impact Testing
  - Free-Free
    Boundary Conditions
  - Eigenmodes
  - 2′ x 4′ Aluminum Plate



Sensors

- Force hammer
- Accelerometers
  - Endevco shock (2 k*g*)
  - PCB triaxial modal (500 *g*)
- PCB piezoelectric strain gages

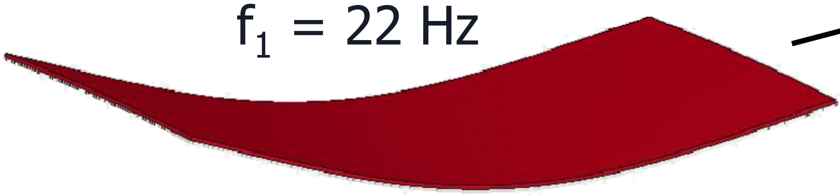
Plate Impact Experiment



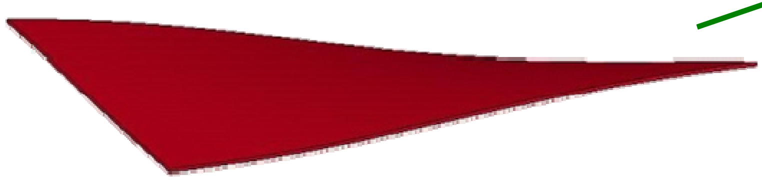
Data Analysis

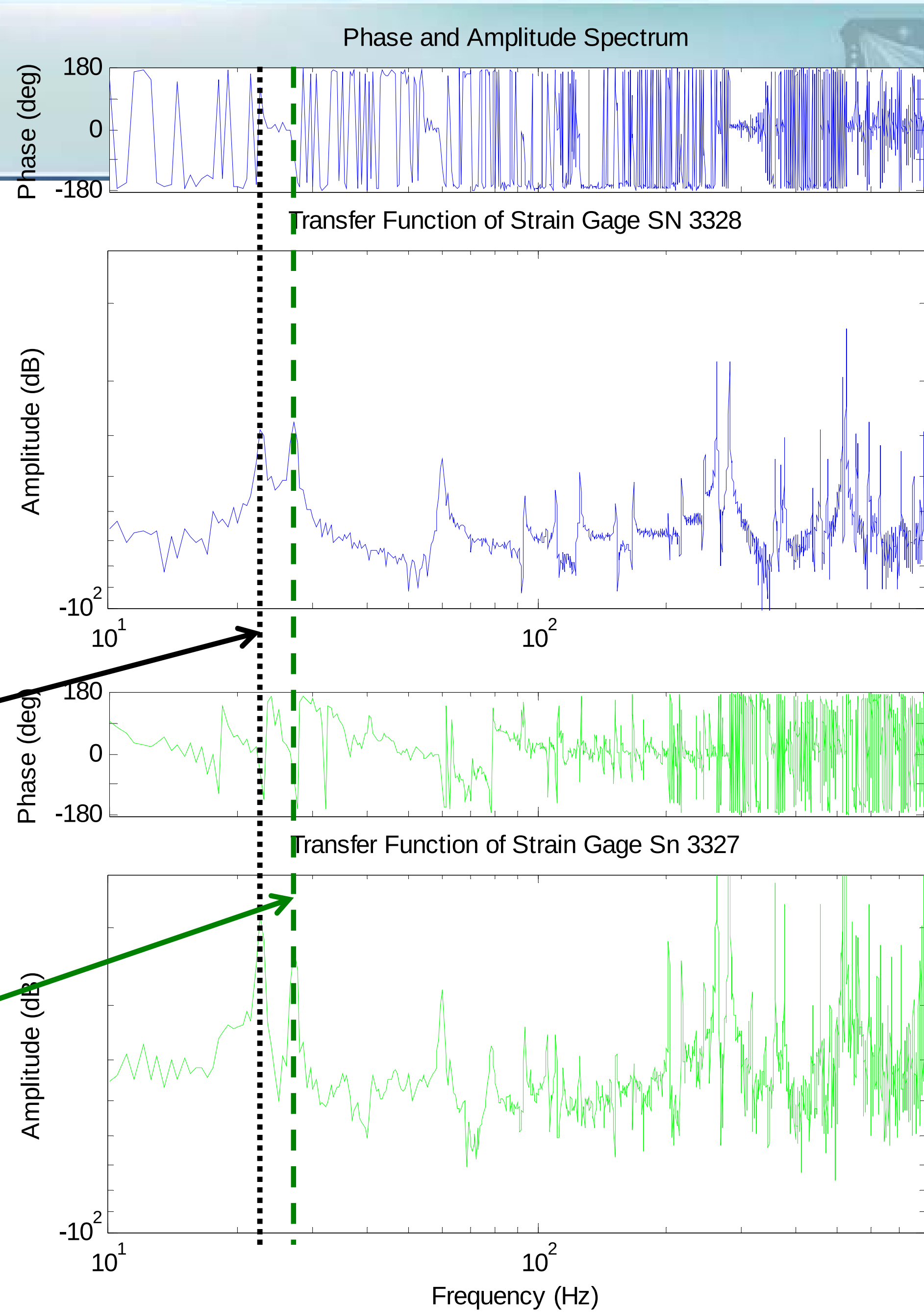
- Transfer functions
  - Force hammer to strain gage output
- Excellent agreement with modal predictions

$f_1 = 22$ Hz



$f_2 = 27$ Hz





Data Analysis

- Initial modal parameter estimation
  - Structural damping (ξ)
  - Eigenvalues
  - Natural frequencies (ω)

- Much work remains for full estimate of modal structure

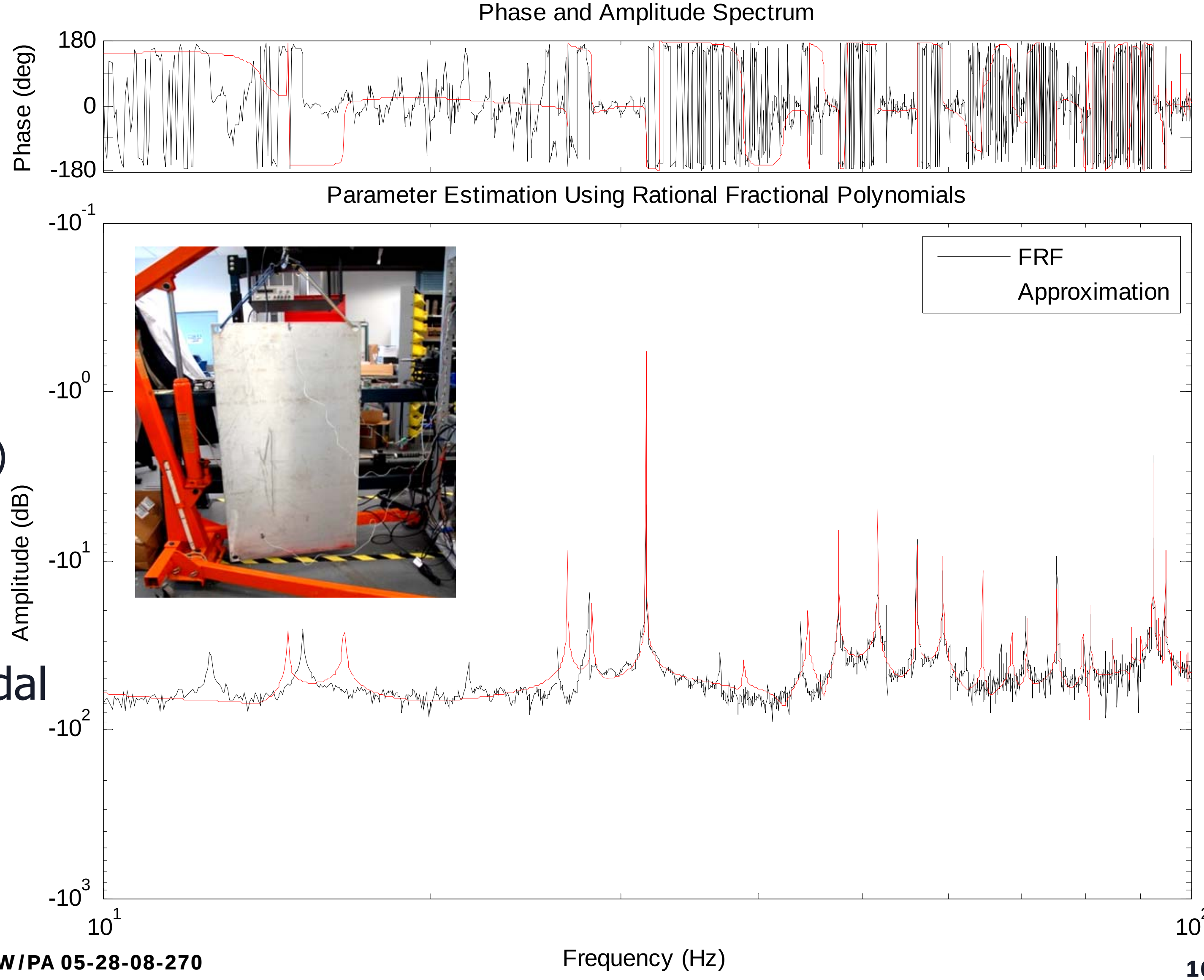


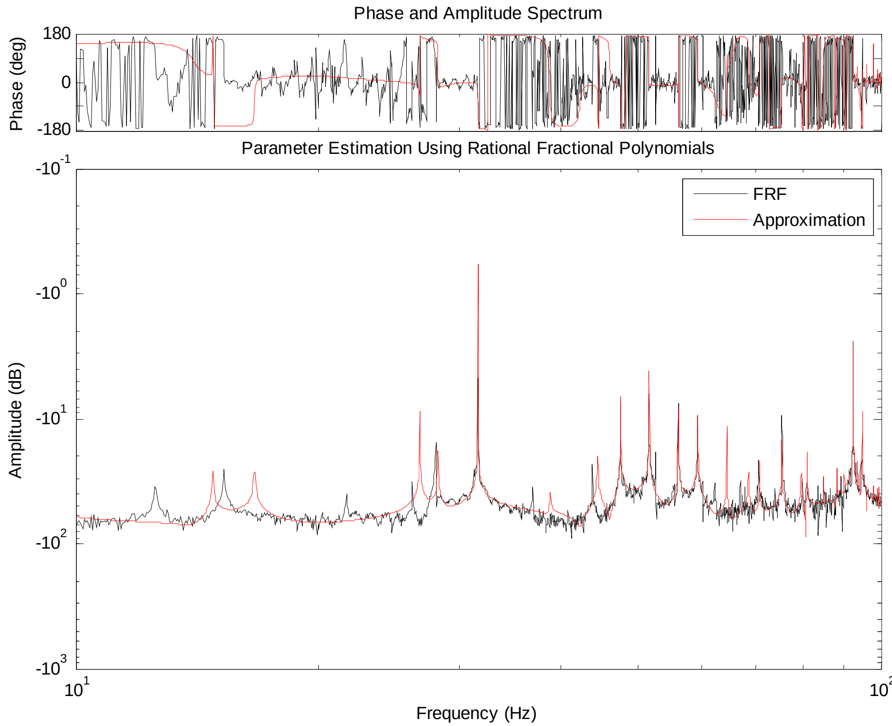
Plate Impact Analysis

Results:

- Model-based estimation of dynamic characteristics from experimental data
- Mode shapes, frequencies extracted from simulations

Assessments:

- Modal structures agree
  – Theoretical (analytic)
  – Simulations
  – Experimental



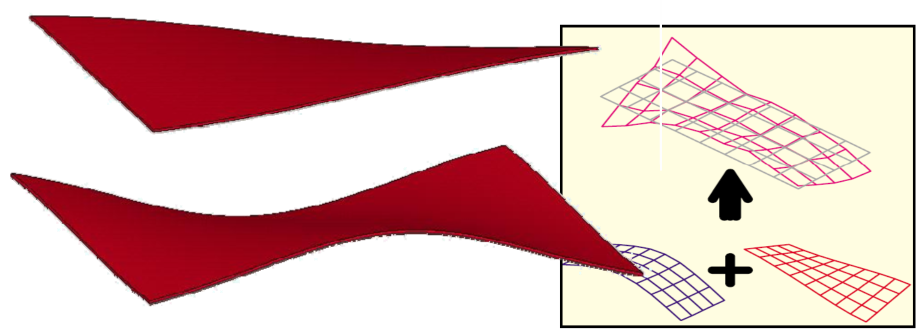


Plate Impact Observations

- Bandwidth vs. record length (again)
- Mode structure is observable in controlled (lab) conditions
- Initial result: models accurately predict linear modes

Future Work:

- Experiment data much higher fidelity and coherence
- Add model-based design of experiments capability for resonating structures
  - Impact- or explosively-driven
  - Beams or plates
- Increase loading rate and amplitude
  - Move to nonlinear regime

Summary

- The dynamic responses of simple mechanical structures—bars and plates—were modeled and experimentally measured
- At low loading rates (linear problem) mode structure is accurately simulated
- Simulations of higher loading rates are indicating lower effective bandwidths
  - Evidence in coherence of experiment vs. M&S
- Future work will focus on further quantifying coherence in structures and developing techniques to increase the effective bandwidth

Acknowledgements

- Dr. Victor Giurgiutiu (AFOSR)
  - Funding (Program Manager)
- Jacobs Engineering
  - Student intern support
- Prof. Alexander Idesman (Texas Tech)
  - Computational results

"Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Air Force."

Questions?

Contact Information:

- Jason R. Foley, Ph.D.
  Mechanical Engineer
  Fuzes Branch, Ordnance Division, Munitions Directorate
  Air Force Research Laboratory
- Phone: 850-883-0584 (DSN 875-0584)
- Email: jason.foley@eglin.af.mil
- Mail: AFRL/RWMF
  306 W. Eglin Blvd., Bldg. 432
  Eglin AFB, FL 32542